Modelling Attempts to Predict Fretting-Fatigue Life on Turbine Components

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Wherever two or more turbine components are in tight contact, Fretting-Fatigue becomes a relevant failure mechanism. Despite of on-going research on Fretting Fatigue, life prediction under fretting conditions continues being a challenge. To analytically predict fretting-fatigue life, key driving factors need to be identified and quantified in mechanical terms (stress and strain). Due to the intrinsic characteristics of contact, stress and strain fields around contact areas evolve with the loading history. They, together with material non-linearity and contact conditions need to be taken into account in order to perform a reliable life prediction.

The present paper focuses on identifying the driving factors for fretting damage on blade-disk attachment under real engine conditions. Two-dimensional finite element contact calculations were carried out to quantify the influence of the key factors on mechanical quantities (stress and strain). Special attention was paid to material models and surface interaction (friction coefficient and contact conditions) in order to balance computational effort with result's accuracy.

Finally, the multi-axial fatigue criteria developed by Dang Van and co-workers is used to predict failure. For validation purposes life prediction is compared with experimental results .

1. THE PROBLEMATIC OF FRETTING/WEAR FATIGUE ON AEROENGINES

1.1. Damage Phenomena Observed

Aero-engines incorporate a large number of mechanical joints, where fretting-fatigue and wear are important life controlling factors. All mechanical components will suffer along their expected life degradation and eventually fatigue. Therefore, Fretting fatigue and wear control need to be considered as a design criteria, even if they may be subsequently dismissed or controlled by design experience or overhaul. Whereas wear is associated with long term operation, fretting fatigue is associated with short term failures (reduced numbers of cycles compared to plain fatigue). Despite of the criticality of both,

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14. ABSTRACT

15. SUBJECT TERMS

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safety requirements on aeronautic components makes prediction and avoidance of fretting-fatigue a critical reliability issue and so it is the focus on current efforts.

Gas turbines, from which aero-engines are a special case, are known to suffer fretting fatigue on components that undergo small relative displacements under high compressive forces, for example blade-disk attachments, splined shafts and in minor degree bolted flanges, see Figure 1 and 2 for typical examples. A classical case, are roots on rotating airfoils. They have to endure high centrifugal forces leading to elevated contact and bulk stress which, combined with relative small displacements that occur as the engine undergoes through its operational cycle, make fretting-fatigue an important, if not the main design criterion. The possibility of blade root failure with its catastrophic consequences makes that any life improvement or at least reliable life prediction has an important bearing on the integrity and overall cost of the engine.

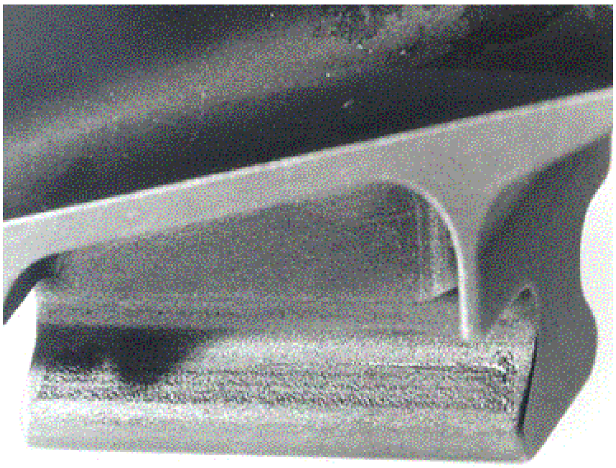

Figure 1. Fretting fatigue failure on a compressor dovetail.

Figure 2. Fretting fatigue induced failure on a casing flange.

Along the years, aero-engines manufacturers and users have collected experience how to control fretting-fatigue and wear. As in conventional fatigue, simple design rules are sufficient to prevent fretting fatigue in most situations [1], but do not provide a quantifiable measure of strength and therefore do not help when it is required to optimize the design or to ensure the integrity of critical components. Many palliative methods have been devised showing a wide variety of effectiveness. They help to overcome critical situations but do not provide a reliable method to prevent and control fretting-fatigue and wear. Despite of research efforts in the last 50 years [2], where the main controlling mechanisms of fretting-fatigue & wear have been identified, a consistent reliable and industry applicable life model continues to be a challenge.

The purpose of the present paper is to explore a life method to predict and quantify a typical fretting fatigue case. Such criteria fulfil the following requirements:

- Based on classic engineering parameters (stress-strain, displacements)
- Can be applied to multi-axial fatigue conditions
- makes use of plain fatigue data
- includes material nonlinearities
- It is computationally tractable.

1.2. Fundamental Aspect of Fretting Fatigue

Fretting Fatigue occurs when two bodies held together undergo a small localized relative displacement, typically of the order of 10-30 µm. It differs from normal wear in that the displacement are much smaller and that any wear debris remains trapped between the two surfaces in contact. Under the contact conditions stated before, a mixed stick-slip regime is established between the bodies. It is well know that fretting-fatigue cracks will develop in the transition zone between stick and slip regions [3].

Crack initiation under fretting fatigue depends mainly on the contact stresses and occurs in the vicinity of the highly localised stress concentration caused by the frictional forces between the surfaces in contact. Crack propagation on the other hand responds to the bulk stress field away from the surface.

Fretting-fatigue damage is also observed to be a function of slip amplitude and bulk stress. Whenever the slip amplitude is big enough, the mechanism of fretting gives way to conventional wear. The net effect is that fretting-fatigue strength decreases with increasing slip (starting from zero) until a point is reached where abrasive wear governs the process and strength increases again.

It is generally recognised that the fretting fatigue process can be divided into three distinct phases:

- Crack initiation
- Short Crack propagation
- Long crack propagation

Due to safety issues, most aeronautic components are designed in such way that they can fulfill their life targets before the long crack propagation regime appears. Then the regime of crack initiation gains significance and proves to be relatively complex to analyze. There is an inevitable dependence on local condition at the contact interface and it may be necessary to consider variables such as material microstructure and asperities.

1.3. Recent Modelling Attempts

During the last 50 years intense research efforts have been devoted to find out the controlling parameters on fretting fatigue. A number of intends have been made to apply global stress or displacement based parameters to the prediction of initiation life. Ruiz et.al. [4] proposed a criteria based on the density of dissipated energy multiplied by the direct stress component parallel to the surface. Hills et.al [5] tested such parameter on different geometries with good results. However the Ruiz parameter is totally empirical and deriving design lines from it, is a difficult task.

More recently, stress based criteria have been proposed, using multi-axial fatigue initiation parameters have been proposed. Szolwinski and Farris [6] have combined the Smith-Watson-Topper approach with the critical plane concept to successfully predict fretting-fatigue experiments assuming an analytical stress situation. Neu et al.[7] have presented a concept to predict fretting fatigue based on fracture mechanics and equivalent crack size to characterize crack initiation. A global approach has been employed by Fouvry et. Al. [8] who have combined a volume averaging method with the Dang Van criterion [9, 10, 11] and have shown that this can give more realistic life predictions for cases where the stress field varies very rapidly.

The above mentioned Dang Van model combined with volume averaging meet the needs stated on paragraph 1.2 and therefore it is the selected model for a first application to an aero-engine fretting fatigue problem.

2. THE DANG VAN MODEL HIGH CYCLE FATIGUE MODEL

The high-cycle fatigue criterion used in the sequel was initially proposed by Dang Van [9-11]. It is based on a multi-scale approach. It is assumed that for an infinite lifetime, elastic shakedown should occur at both the macroscopic and the mesoscopic scales. The macroscopic scale is characterized by an arbitrary elementary volume surrounding the point where the fatigue analysis is conducted, representing for instance an element of finite element mesh; it is the usual scale considered by the design engineers. The mesoscopic scale corresponds to the scale of crystalline grains. The stress tensors at both scales are related through a localization tensor and eventually a mesoscopic residual stress tensor, due to a mesoscopic inelastic strain.

The elastic shakedown assumption at the local scale, permits to estimate the local stress cycle from the macroscopic stress cycle. The criteria is then expressed as an inequality relating the mesoscopic shear and pressure on slip planes at all instants of the cycle, so that damaging loading can be precisely characterized. The usual form of the criterion is:

$$\max_t \tau(t) + a\, p(t) < b$$

where $\tau(t)$ and $p(t)$ are the instantaneous mesoscopic shear stress and hydrostatic stress and a and b are material constants, to be determined by two different classical fatigue tests (for example reversed traction and torsion).

If the inequality is satisfied, the corresponding material volume is subject to an infinite lifetime under the prescribed loading. If not, a crack will initiate and the structure will fail after a number of cycles which is proportional to the extent by which the criterion was overrun.

In order to apply the criterion on a structure different steps have to be performed:

- the first step is *a complete elasto-plastic analysis* under cyclic loading. The result *should asses that the structure is macroscopically under an elastic shakedown state* in all its points. If a plastic shakedown state is found in a series of points a low cycle failure should be expected and criteria related to the dissipated energy or the inelastic strain should be applied. For a general overview of the passage between the high cycle and the low cycle fatigue domains see [12].

- The second step is the fatigue analysis, in which the fatigue criterion is checked in all points of the structure. Two different techniques can be applied:
  - the load path is represented in a (p, τ) diagram. The two constants a and b define a line, and as such a safety domain: no cracks and infinite lifetime under the line and fatigue and crack initiation otherwise.
  - The evaluation of the maximal distance of the points of the loading path from the fatigue line, through the evaluation of: $\max_t (\tau(t) + a\, p(t) - b)$ permits to conclude that fatigue will occur if the distance is positive and to estimate a number of cycles to failure from this quantity.

This methodology has already been succesfully applied in a series of industrial application. A general review is given in [13]. We shall only point out an application to rolling contact in [14] and an application to fretting-fatigue experiments in [15-17]

3. SELECTED TEST CASE: TURBINE SPIN-PIT TEST

3.1. Test Description

The test case used for the validation of the model is a spin-pit test performed on a turbine disk configuration. The disk is fitted with 47 blade “dummies” that are connected to the disk by a firtree-type attachment geometry. The contact flank on the dummy is barrel-shaped, whereas the disk contact flank is flat. For ease of manufacturing of the spin test arrangement, the dummies do not resemble the real airfoil geometry, but use a bulk mass equal to the airfoil mass to exert the equivalent rim load to the disk.

The reason why a spin test arrangement is especially useful for the validation of an analytical fretting fatigue model lies in the fact that all test parameters are very well monitored and controlled: the test runs under vacuum, at a constant elevated temperature of 650°C and the disk is spun in mini-cycles varying the rotational speed from idle to maximum conditions. Furthermore, unlike real engine conditions, there are no additional vibrational loads exerted on the dummy due to the fact that the test is run under vacuum.

The blade dummies and the disk are both manufactured from standard nickel based alloys. The disk material is a very high strength alloy whereas the dummy material shows a much lower yield limit. Nevertheless the strain to rupture exceeds 18% for both alloys. Figure 3 shows the relation of the monotonic stress-strain curves for both alloys in a non-dimensional diagram.

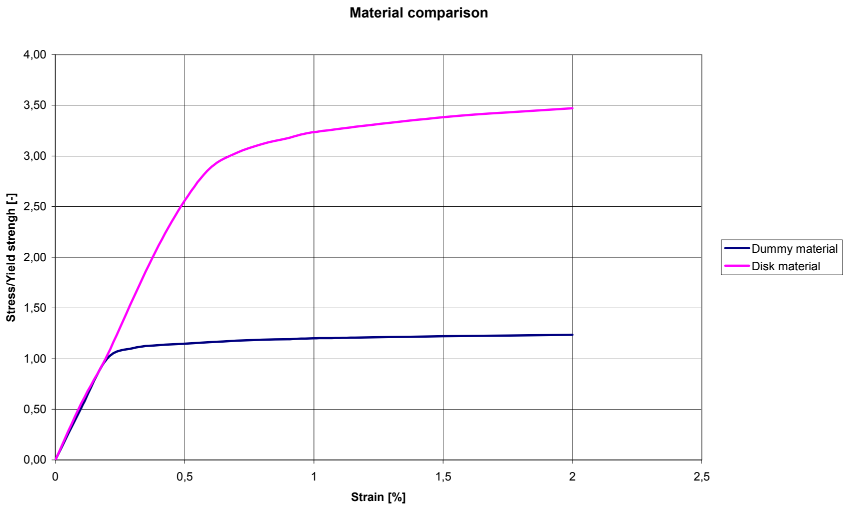

Figure 3: Comparison of stress-strain curves for disk and dummy material.

3.2. Computational model:

A two-dimensional computational finite element model was employed to derive the stress and strain fields in the contact zone of the disk and the dummy, assuming the simplification of a plane strain state, which is reasonably correct for the centre portion of the attachment. For the sake of simplicity only one half of the attachment was modelled to make use of the symmetric geometry.

An isotropic hardening model was used to simulate the material non-linearity and the cyclic hardening behaviour of the two alloys. The calculation was run for 10 consecutive loading cycles to converge to a stable shakedown state. To evaluate the effect of the friction coefficient on fretting fatigue life, several computations were performed with varying μ values ranging from 0 to 0.9.

3.3. Results

Figure 4 shows the stress distribution on the outer contact lobe of the attachment during the 10th loading cycle for a friction coefficient of 0,3. From this plot it is obvious that the highest stresses occur on the trailing edge of contact on the disk side.

Figure 5, on the other hand, shows the distribution of equivalent plastic strain for the same number of cycles. It can be seen clearly, that yielding is only present on the dummy side of the arrangement. The high amount of plastic deformation also explains that the contact stresses on the dummy are relatively low, due to stress redistribution.

Here it should also be pointed out, that the highest amount of plastic deformation is located on the leading edge of the contact on the dummy side. Even though the part suffers considerable initial plastic deformation, the cyclic stress-strain response is asymptotic, i.e. a shakedown state is reached after a sufficient number of cycles, as it is depicted in Figure 6.

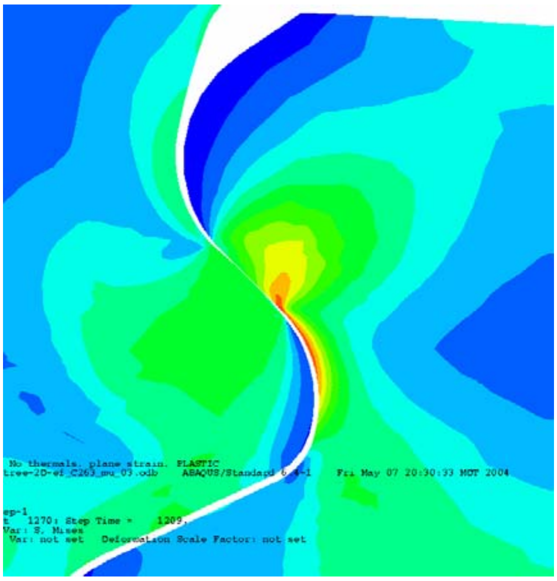

Figure 4: Distribution of equivalent stress after 10th loading cycle for μ=0.3.

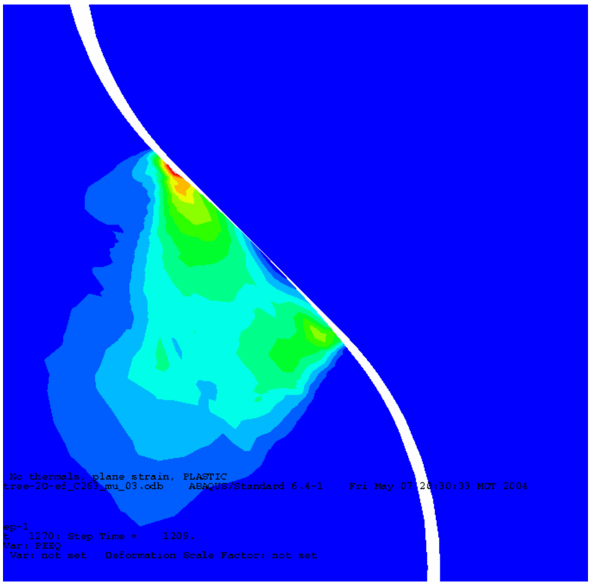

Figure 5: Distribution of equivalent plastic strain after 10th loading cycle for μ=0.3.

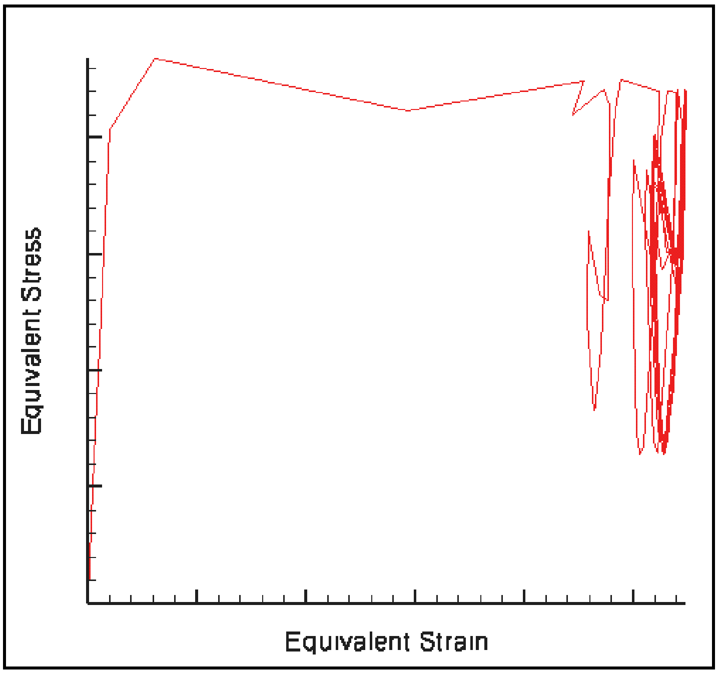

Figure 6: Material Stress-Strain response for critical location on the dummy for 10 consecutive cycles.

The fact that an elastic shakedown state is reached in the material response, permits to make use of the Dang Van multi-axial lifing criterion for HCF. It uses the stress tensor for each point at each load increment as an input and plots the loading path for the stabilized cycle divided into a hydrostatic pressure σ_h and a maximum mesoscopic shear component τ on the critical plane. This loading path is then compared to the material fatigue limit for 10^7 cycles. If the loading path crosses the material fatigue limit at some point during the loading cycle, crack initiation is expected, or in other words: the component has limited fretting fatigue life.

Figures 7 show the Dang Van loading paths on the critical disk locations for μ-values of 0, 0.3 and 0.9 at one of the critical locations (inner disk lobe). From the plot it is evident, that for no friction (μ=0) no crack initiation is expected, as the loading path does not cross the material fatigue line at any instant during the loading cycle. In contrary, for higher friction coefficients (μ=0.3/0.9), the loading path crosses the fatigue line during the *loading* phase.

Figure 8 shows the evolution of the loading path with depth normal to the surface at the critical location of the inner disk lobe. It can be noticed that the loading remains critical even slightly below the surface.

The corresponding critical locations determined by the Dang Van criterion lie on the trailing edges of contact on the disk surface, as it is depicted in Figure 9.

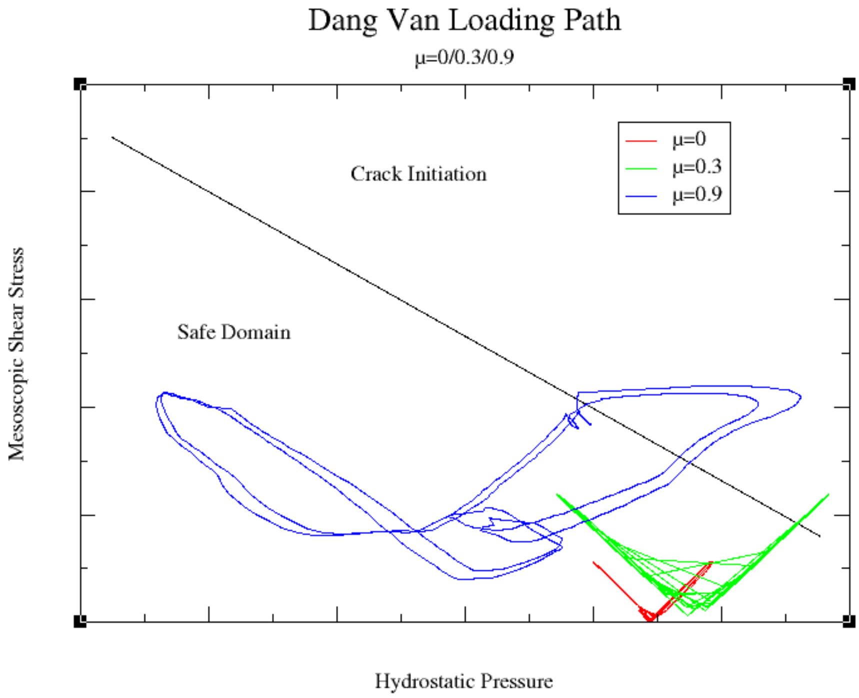

Figure 7: Dang Van Line for critical locations on the disk surface for μ=0, 0.3 & 0.9.

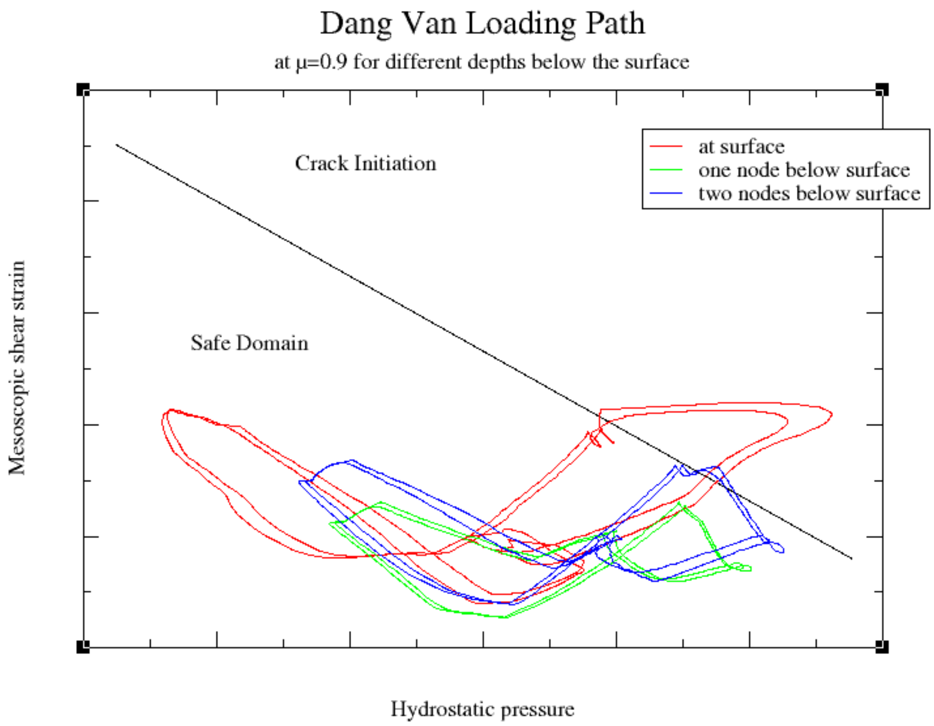

Figure 8: Dang Van Line at critical locations for different normal depths.

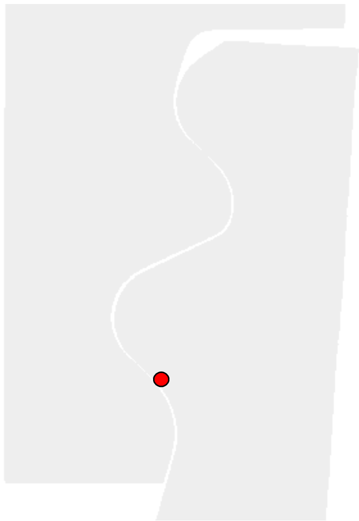

Figure 9: Critical locations on the disk surface determined by the Dang Van criterion.

This results matches very well with experimental observations on the spin-pit test as can be seen in Figure 10. A metallurgic investigation of the cross section shown in Figure 11 puts in evidence that the crack starts growing from the trailing edge of the contact zone.

The fact that the application of the Dang Van multi-axial fatigue model was able to correctly predict the failure location on the disk side of the contact must be highlighted at this point, as this phenomenon was not discovered by design criteria employed at present.

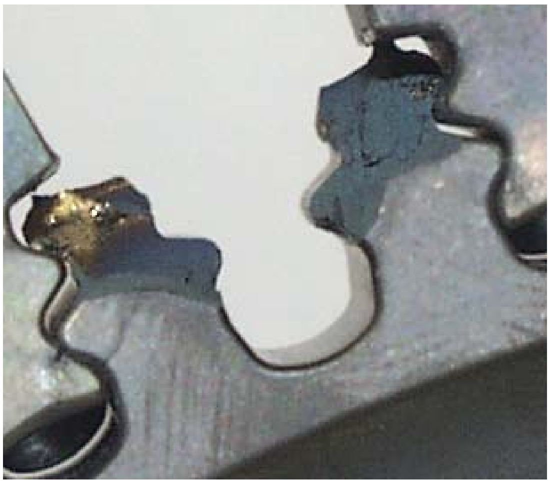

Figure 10: Crack location observed during the spin pit test.

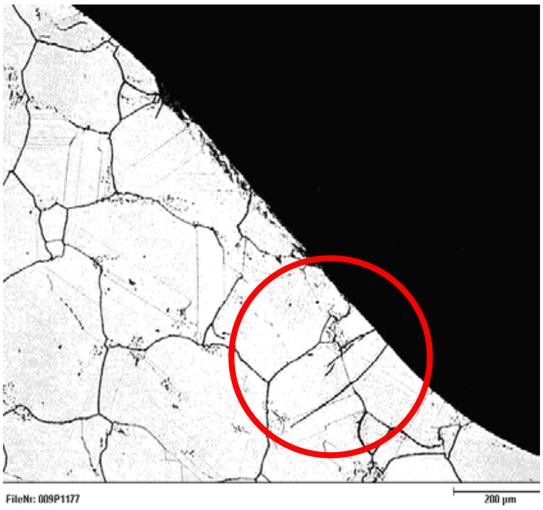

Figure 11: Micrographic picture of crack location, right outside of the contact area.

4. DISCUSSION AND FUTURE DEVELOPMENTS

Quantitative prediction of fretting fatigue on structures and more specifically on turbine components is a key issue in engine design. In spite of large research efforts in the last decades this problem has not yet been tackled in a satisfactory way. The current methods are essentially based on direct structural testing which demand high costs and long duration and conduct only to empirical models.

The methodology proposed in this work is based on the one hand on a direct evaluation of the local mechanical state by efficient numerical computations including contact phenomena and on the other hand on the use of a multiaxial fatigue criteria, independent of the fretting or contact phenomena.

The validity of this proposal has been checked using results from an experimental rig. It has been shown that the methodology

- is able to predict correctly the zone of crack initiation at the end of the contact zone
- is also able to distinguish between damaging and non-damaging load conditions with the variation of the friction between the two components.

In order to apply this methodology as a complete design technique in an engineering environment, further extension should be attained:

- for the fatigue analysis: a precise estimation of the number of cycles to failure when the Dang Van criterion is overrun, as well as a lifetime estimation when plastic shakedown occurs. Both methods should also be extended to estimate damage created in a series of tests.
- For the mechanical analysis: an assessment of the stabilized shakedown cycle by direct computation in cases when contact does occur.

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